

Tilted plateau in nuclear collisions: data, models and MC-s

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Abstract

The linear dependence of the particle spectra on rapidity is seen in the central region for asymmetric heavy ion collision in the data and in the Monte Carlo results, similarly as in the fragmentation region for hadronic and ion collisions. The origin of such a behaviour is discussed. It is shown that the color string models produce naturally such a shape if string ends are randomly distributed in rapidity.

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1 Introduction

Recently, there has been a renewed interest in the energy dependence of multiplicity of hadrons from the multiparticle production processes. In particular, the possibility of understanding some regularities observed in data as the consequence of simple assumptions on the production mechanism was considered.

In this note we discuss the shape energy dependence of the distributions in CM rapidity

$$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$

and CM pseudorapidity

$$\eta = -\ln \operatorname{tg}(\theta/2)$$

for charged pions and other hadrons produced in the nuclear, p - p and e^+e^- collisions. We present distributions obtained from the Monte Carlo generators and compare them with some data and simple rules expected from various assumptions. Some remarks on the possible generality and universality of production mechanism are given.

First, let us remind that the rapidity distributions have many advantages as the tools for the discussion of the energy dependence of multiparticle production providing more details than just the average multiplicity. The shape of rapidity distribution is invariant under the Lorentz transformation along the longitudinal axis and changes rather slowly with energy. This was the original motivation for the Feynman hypothesis of a "plateau" in rapidity with an energy independent height (based on an analogy with electromagnetic bremsstrahlung). Since the integral of a single-particle inclusive distribution is equal to the average multiplicity, the "plateau" hypothesis leads to the logarithmic increase of average multiplicity. Similarly, the generalization of Feynman hypothesis to the multiparticle distributions leads to the KNO scaling for the multiplicity distributions.

Today we know that Feynman hypothesis was wrong. There is no "rapidity plateau" of a fixed height; the rapidity distributions resemble rather Gaussian curves with both height and width increasing with energy. The average multiplicity grows with energy faster than logarithmically, and KNO scaling is also not exact. Still, there seem to be other simple regularities in the rapidity distributions.

The rapidity distributions for asymmetric nuclear collisions are particularly interesting. Naive expectations were those of "two plateaus" differing by height and smoothly connected for particles which are slow in the CM frame. In the data, however, we see instead a complicated structure resulting in the "tilted plateau" (i.e., linearly decreasing function of rapidity) for the ratio of d - Au to the p - p data. We discuss here in more detail this and some other regularities seen in the recent data on d - Au collisions [1], [2], comment on their interpretation within the wounded nucleon model [3] and compare them with the predictions of the default version of the FRITIOF Monte Carlo generator [4], [5].

Before starting this discussion we analyze another rapidity range in which a similar linear decrease of spectra in rapidity was observed: the fragmentation region in hadron-hadron and nuclear collisions. It is well known that in this case another Feynman hypothesis works well: scaling (i.e. the energy independence) of the distribution in "Feynman x variable", $x = p_L/p_L^{max}$, which is approximately valid for $x \neq 0$ (more precisely, for x significantly bigger than m/\sqrt{s}). It is easy to check that it means energy independence of

the distribution in $y^{max} - y$ for moderate values of this variable. This does not determine the shape, nor does it answer the simple question: is the range of scaling in $y^{max} - y$ (or $y - y^{min}$) energy independent, or does it extend logarithmically with energy, as the full range in rapidity does? In this note we address these questions for the data [6], for a simple model [7] and for the events modelled by PYTHIA [8] and FRITIOF [4], [5] generators. As mentioned above, in the fragmentation region of $p - p$ collisions a similar linear dependence on rapidity is observed as in the central region of asymmetric nuclear collision. We comment on the origin of this similarity in the models underlying Monte Carlo generators.

2 Fragmentation in the $p-p$ and heavy ion collisions

In Fig.1 and Fig.2 we show the PYTHIA results for the $p-p$ collisions at CM energies of 50, 200, 550 and 900 GeV .

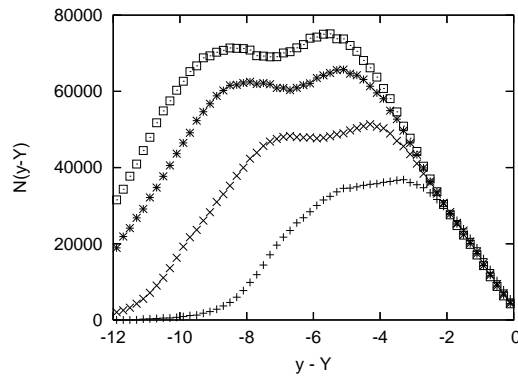


Figure 1: *PYTHIA* results for the charged pion distributions in the $p-p$ collisions at CM energies of 50, 200, 550 and 900 GeV (crosses, x-s, stars and squares, respectively).

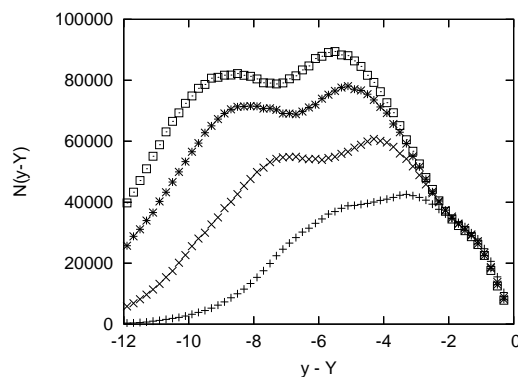


Figure 2: *PYTHIA* results for the charged pions, kaons protons and antiprotons distributions in the $p-p$ collisions at CM energies of 50, 200, 550 and 900 GeV (crosses, x-s, stars and squares, respectively).

The horizontal scale is $\eta' = \eta - y^{beam}$; thus all the consecutive plots are shifted so as to assure that the scaling corresponds to the energy independence of the right-hand end of the distribution. In Fig.1 only the charged pions are counted, whereas in Fig.2 charged kaons, protons and antiprotons are also included. We see that there is an approximate scaling, and the range of scaling in η' increases with energy, but not as fast as the full pseudorapidity range; the range of the "plateau" increases as well. It is interesting to note that by counting only pions we get almost exactly linear behaviour of spectra in the "scaling range", whereas for the "all charged" selection the points are less regularly distributed.

In Fig.3 the ISR and collider UA5 data [6] at similar energies (53, 200, 546 and 900 GeV) are shown in the same variable η' . We do not compare them directly with MC results, since the involved procedure of removing the UA5 detector effects is difficult to analyze. However, detailed inspection shows that the scaling seems to be broken more significantly than in Fig.1. The range covered by data depends on energy, but the slope with which the distribution falls at $\eta' \rightarrow 0$ increases with increasing energy, which was not seen for MC results.

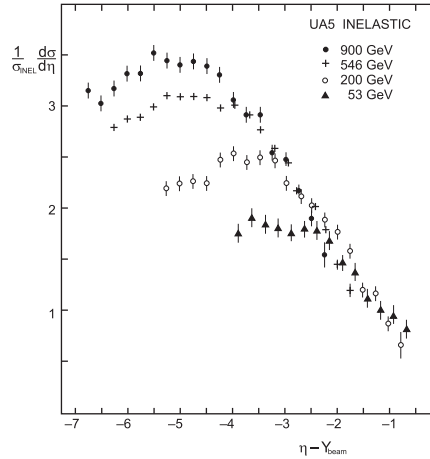


Figure 3: *ISR and UA5 results [6] for the charged hadron distributions at CM energies of 50, 200, 550 and 900 GeV (triangles, circles, crosses and dots, respectively).*

Similar approximate scaling is observed in the rapidity spectra from heavy ion collisions. As an example of the results from the MC calculations for such collisions we show in Fig.4 the distributions obtained from the FRITIOF generator for the central S - S collisions. The sample was defined by requiring more than 20 participants (out of 32 nucleons) for the forward going ion. This condition is satisfied by 11-13% of events; the percentage is slightly increasing with energy. We see that there is an approximate scaling for the range increasing with energy, and the shape of the distribution in this range is again linear.

The recent data concerning rapidity distributions from the heavy ion collisions were presented by PHOBOS collaboration [2]. The data collected at three energies for the most central Pb - Pb collisions (6% of the full sample of events) are shown in Fig.5. Their behavior is qualitatively identical to that of MC results from Fig.4.

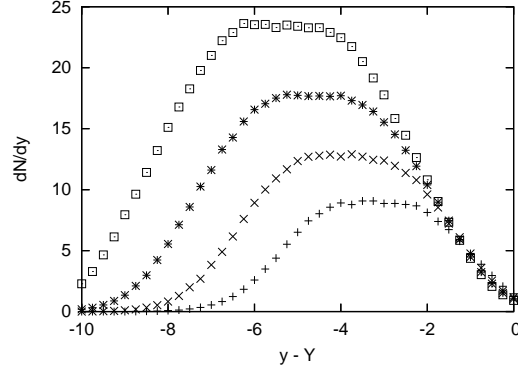


Figure 4: *FRITIOF* results for the charged pions distributions in the *S-S* collisions at *N-N* CM energies of 20, 40, 80 and 160 GeV (crosses, x-s, stars and squares, respectively).

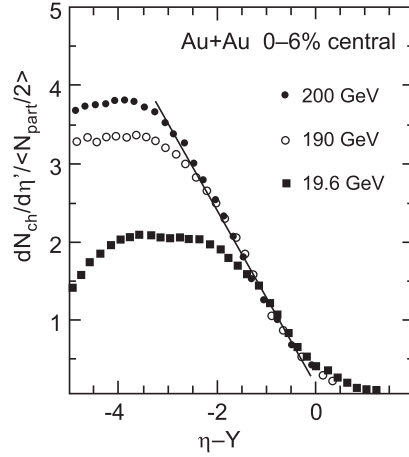


Figure 5: *PHOBOS* results for the charged hadron distributions in the *Au-Au* collisions at *N-N* CM energies of 19.6, 130 and 200 GeV (squares, circles and dots, respectively).

It is interesting to note that an approximate scaling, a linear dependence of spectra on rapidity in the fragmentation region and the increase of the range of such behavior with energy are not seen in the simplest production process: e^+e^- annihilation into hadrons. Obviously, there are many problems when comparing this process with hadron- or heavy ion collisions. To define rapidity, one needs to know the collision axis. It may be defined as the sphericity or thrust axis, but the estimate of the direction of this axis for some events may be poorly determined. The alternative is to define a sort of "energetical rapidity" independent on the direction of particle momentum. In both cases we tried unsuccessfully to establish scaling in the MC results for the fragmentation region, even for the restricted range of energies. One may attribute it to the thresholds for heavy quark production and/or energy dependence of the multijet fraction of events. This should be kept in mind when discussing the possible interpretation of the effect.

The approximate scaling with the linear dependence on rapidity for the hadron-hadron and heavy ion collisions was recently explained by a simple model motivated by the nonabelian bremsstrahlung effect [7].

In this model the first stage of the hadroproduction process consists of consecutive color exchanges between the pairs of partons from two colliding hadrons. The created color charges emit the final state hadrons by the bremsstrahlung process (uniformly in rapidity). If the initial partons are also uniformly distributed in rapidity (which corresponds to the $1/x$ spectrum in Feynman x variable), the resulting distributions in the fragmentation region fall linearly with the rapidity variable $y - Y_{max}$, as seen in the data.

The limit of the linearity regime is determined by the condition that interacting partons must live longer than for some fixed time τ_0 , necessary to complete the color exchange. Then the linear increase of the spectrum stops at some rapidity y_0 , depending on τ_0 and on the parton transverse mass. In the central region a plateau in rapidity appears. Obviously, this picture is frame dependent; assuming arbitrarily that the assumptions are fulfilled in the CM frame (which seems to agree with the data) one breaks explicitly the boost invariance.

Therefore one may prefer another formulation of the model, in which the bremsstrahlung process is replaced by the breaking of color strings spanned between a parton from the projectile and a parton from the target. In this case the plateau in the central region appears as a result of the assumption of minimal energy of a string, corresponding to the minimal difference in rapidities of the partons at the ends of the string. There are no very short strings (slow in the CM frame), which would result in the linear increase of spectra down to the CM rapidities close to zero.

The linear decrease in the fragmentation region may be easily understood if we write down the spectrum as the result of an integral over the string end distribution. For small $y_{max} - y$ we get

$$\rho(y) = \int \bar{n}_s \kappa \theta(z - y) \rho_s(z) dz$$

where \bar{n}_s is the average number of contributing strings, $\rho_s(z)$ the distribution of the string end, and $\kappa \theta(z - y)$ is the distribution of hadrons from a single string. If $\rho_s(z) = const$, one gets linear $\rho(y)$.

It appears that the presented picture approximates well the models underlying the Monte Carlo generators used in the previous section. In the PYTHIA generator there are indeed many strings formed in each hadron collision, and the distribution of the ends of most of them obeys the $1/x$ distribution. Thus it is not surprising that the results from this generator (shown, eg., in Fig.1) agree reasonably well with the data shown in Fig.3. For the heavy ion collisions at moderate energies the FRITIOF generator uses just two strings for each nucleon collision. However, in this generator the distribution from a single string is non-flat for the major part of rapidity range, and a superposition of strings from different nucleons appears to produce approximate linearity of the distribution in this case as well.

3 Asymmetric nuclear collisions

Recently, the PHOBOS collaboration presented new data on d - Au collisions at RHIC energy [1], [2]. The data are divided into five equally populated centrality bins, ranging

from the most central to the most peripheral events. Considering the ratios of the rapidity spectra for these five samples to the p - p data

$$R(y) = \frac{dN^{d-Au}/dy}{dN^{p-p}/dy}$$

one observes the simple pattern, as shown in Fig.6.

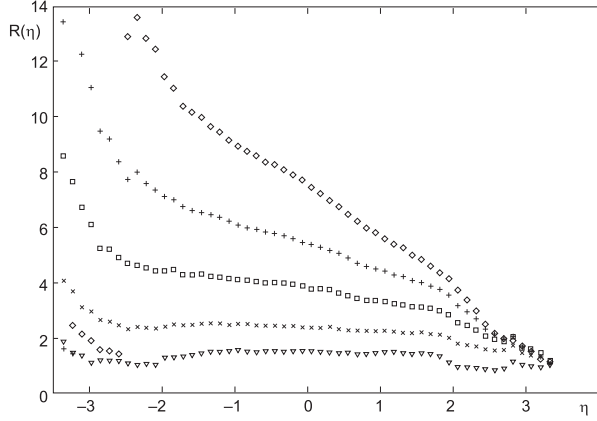


Figure 6: *PHOBOS* results [1],[2] for the ratio $R(y)$ as a function of pseudorapidity for 5 centrality bins (20% each), ranging from most peripheral (triangles) to the most central ones (diamonds).

For a rather wide range of rapidities the ratio decreases linearly, and the slope is determined by the average number of participants ("wounded nucleons") in the Au nucleus for the given centrality range $w_{Au}^{(c)}$. The deviations from the linear dependence are seen for large negative rapidities (i.e., in the Au nucleus fragmentation region, where the nuclear cascade effects are needed to describe the data), and near the kinematical limits.

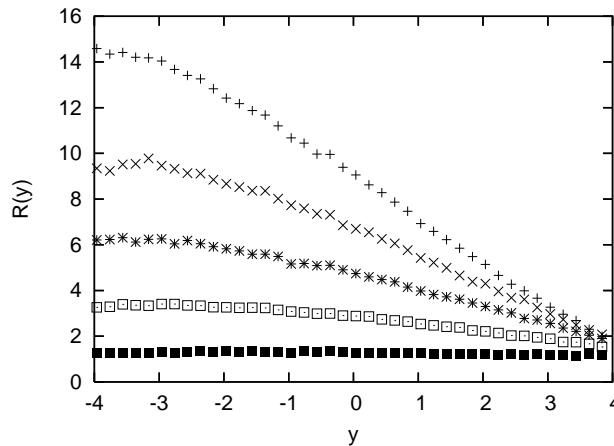


Figure 7: *FRITIOF* MC results for the ratio $R(y)$ as a function of pseudorapidity for 5 centrality bins (about 20% each), ranging from most peripheral (black squares) to the most central ones (crosses).

We have checked that qualitatively similar results (Fig.7) come out from the FRITIOF generator, where the color strings are assumed to form from each "wounded" nucleon. Precisely speaking, not all the strings in this model are identical: the strings from the "multiply wounded" nucleons are slightly longer and produce more particles, but this is a "second order correction". The origin of the linear dependence on rapidity in this model is thus quite obvious: the "slow ends" of strings are uniformly distributed in rapidity ($1/x$ distribution in Feynman x variable), the distribution from a single string is approximately flat and the number of strings in each CM hemisphere is just the number of wounded nucleons. In fact, the linearity is much better for the " d -Au"/" p - p " ratio, than for the rapidity spectra, as the "non-flatness" effects for single string in the d -Au and p - p collisions approximately cancel in the ratio.

We did not compare directly the data shown in Fig. 6 and the MC results shown in Fig. 7. One of the reasons is the absence of the nuclear cascade in the FRITIOF MC. Thus for $y < -2$ the data curve upwards, and the MC downwards. Also the centrality bins were not exactly the same for both figures. However, we see clearly that the MC results reproduce well the "tilted plateau" with the slope proportional to the number of wounded participants.

The PHOBOS data were recently analyzed within the framework of the wounded nucleon model [3]. In this model the symmetric and antisymmetric components of the particle density

$$G^\pm(\eta) = \frac{dN(\eta)}{d\eta} \pm \frac{dN(-\eta)}{d\eta}$$

are proportional to the average symmetric and antisymmetric single nucleon contributions $\langle \Phi^\pm(\eta) \rangle$, which may be reconstructed from the data

$$\langle \Phi^\pm(\eta) \rangle = \frac{\sum_c G^{(c)\pm}(\eta)}{\sum_c [w_{Au}^{(c)} \pm w_d^{(c)}]/2}$$

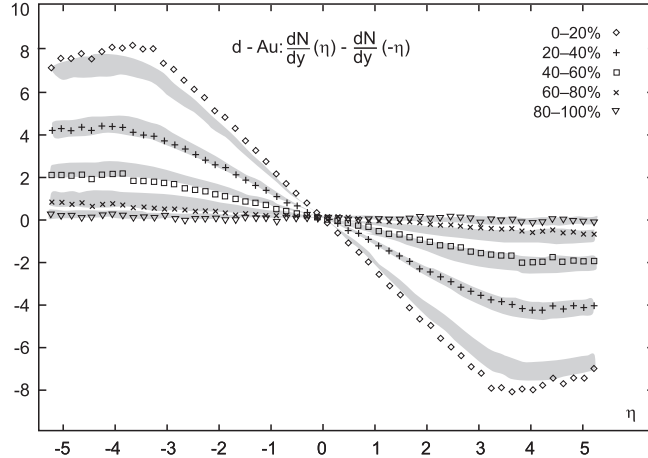


Figure 8: The antisymmetric part of the d -Au inclusive spectra in pseudorapidity from PHOBOS compared with the predictions of wounded nucleon model for five centrality bins [3].

For each centrality we get

$$G^{(c)\pm}(\eta) = \frac{w_{Au}^{(c)} \pm w_d^{(c)}}{2} \langle \Phi^\pm(\eta) \rangle .$$

In Fig.8 and Fig.9 [3] the model predictions are shown as grey bands and compared with data for five centrality bins. For the antisymmetric components there is a qualitative agreement, although the centrality dependence is underestimated: for peripheral events the data are closer to the axis than the predictions, and for central events they are further from the axis. For the symmetric component the agreement is better, although there appears a similar trend.

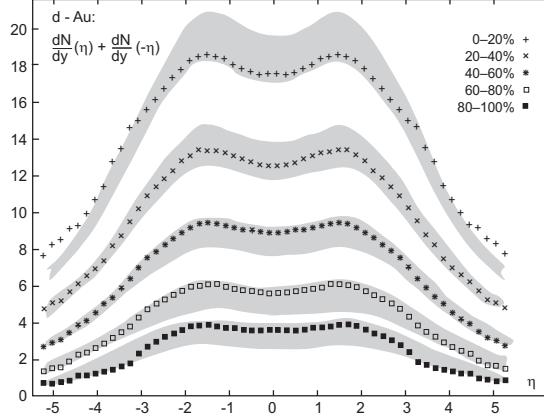


Figure 9: The symmetric part of the d -Au inclusive spectra in pseudorapidity from PHOBOS compared with the predictions of wounded nucleon model for five centrality bins [3].

The average over centralities $\langle \Phi^\pm(\eta) \rangle$ is meaningful only if separate contributions from different centralities do not differ to much. We checked that for the FRITIOF MC the scaling of $G^{(c)\pm}/(w_{Au}^{(c)} \pm w_d^{(c)})$ is approximately valid – the deviations for most peripheral events are due the improper estimate of w_d in our sample. This is shown in Fig.10 and Fig.11, where the p - p data are shown for comparison (crosses).

We see that the FRITIOF generator (based on the string picture) gives qualitatively the same results as the wounded nucleon model. One should stress that the contributions from a wounded nucleon as extracted from the data [3] extend quite far in the "wrong" CM hemisphere. The same apparently happens for single string contributions in FRITIOF. The flat distribution of the string ends extends far in both hemispheres.

The "tilted plateau" in the symmetric nuclear collisions is easy to understand in the string models. Let us assume that there are w_A strings from the wounded nucleons in nucleus A and w_B strings from nucleus B , each string producing flat rapidity spectrum and the "slow" string ends (in CM) are randomly distributed in rapidity within the range from $-\Delta$ do $+\Delta$. We get (for y in the same range)

$$\rho(y) = \int \kappa[w_A\theta(z_1 - y) + w_b\theta(y - z_2)] \frac{dz_1 dz_2}{4\Delta^2} = \kappa[w_b + (w_A - w_b) \frac{\Delta - y}{2\Delta}]$$

and

$$R(y) = [w_b + (w_A - w_b) \frac{\Delta - y}{2\Delta}]/2$$

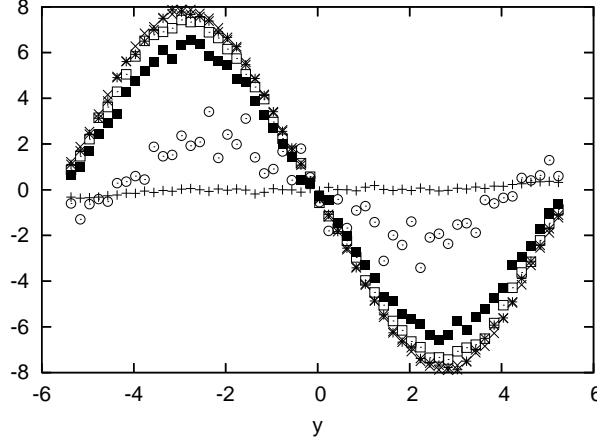


Figure 10: *The antisymmetric part of pseudorapidity spectra for d -Au collisions from the FRITIOF generator for five centrality bins, scaled by the difference $w_{Au} - w_d$.*

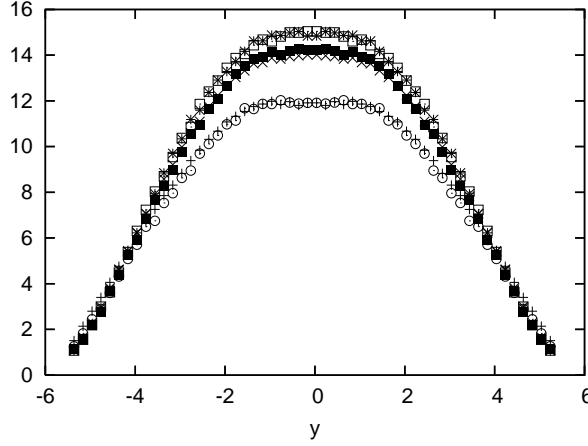


Figure 11: *The symmetric part of pseudorapidity spectra for d -Au collisions from the FRITIOF generator for five centrality bins, scaled by the sum $w_{Au} + w_d$.*

Note that the two integrations are independent and one may use a single integration variable z instead of two, apparently assuming that the strings from both sides always merge. This description is a fair approximation to the data (Fig.6) and to the results of FRITIOF (Fig.7), when $\Delta \approx 3$ and the experimental values of w_A and w_B for each centrality are used. As noted above, this suggests the strings related to each nucleus extend far into the "wrong" CM hemisphere.

4 Conclusions and outlook

We have discussed rapidity spectra from the hadron-hadron and nuclear collisions. The recent observation of linearly decreasing spectra in the fragmentation region and its interpretation in a simple model based on the idea of nonabelian bremsstrahlung were recalled and the string version of this model was shown to account for the successes of Monte Carlo

generators in the data description. The main subject of our discussion were, however, the rapidity distributions in the central region from the asymmetric heavy ion collisions. Reinterpreting the successes of wounded nucleon model in the language of string model we have shown that the origin of "tilted plateau" in this case is the same as that of the linear decrease in the fragmentation region: superposition of many "mini-plateaus" from single strings with a uniform distribution of the string ends. Again, this accounts for the successes of Monte Carlo calculations using generators with the appropriate description of string generation and decay.

It is interesting to note that the scaling in the fragmentation region with the linearly decreasing rapidity spectra is not observed in the simplest hadroproduction process: e^+e^- annihilation. At the first sight it seems to contradict the idea of "non-abelian bremsstrahlung mechanism", which should be observed in the purest form for the $q\bar{q}$ final state. However, in the string picture the linear decrease results from the uniform string fragmentation and from the uniform string end distribution. The first is true for the $q\bar{q}$ final state, but the second condition is not fulfilled. The detailed investigation of the shape and energy dependence of the rapidity spectra from the e^+e^- annihilation would be valuable, especially with the separation of the final state quark flavors and two jet events.

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